A Study of an Actuator Utilizing Thermoelectric Elements(熱電素子を用いた運動素子に関する研究)

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論文内容要旨

Chapter 1. General Introduction and Background

In this chapter, the background and the objectives of this study are stated, and the organization of the thesis is described. Moreover, previous researchers related to this study are also reviewed.

Shape memory alloy(SMA) has a shape memory effect(SME), which deforms depending on temperature variation. Two-way SME realizes repetitive deformation by the continuous heating and cooling. This effect is utilized in moving mechanics of actuators because of its simple mechanism. On the other hand, Peltier element consists of thermoelectric semiconductors can generate large Peltier effect, which can transport heat when electric current was applied. Also the heat transport direction of Peltier effect is inversed by the inversion of the applied current direction. Therefore, Peltier elements are utilized as compact heat transfer device.

Heating and cooling of SMA is needed to utilize SME in actuators. Joule heating and convectional cooling is conventionally utilized because of its simple mechanics. However, the convectional cooling is resulting in slow response of the actuator. Downsizing of the SMA can increase cooling rate of itself, but the deformation force is reduced.

Some research studies about an actuator combined SMA and thermoelectric semiconductors have been reported in literatures. This combination can increase cooling rate of SMA. However, the fabrication of actuator, which works in rapid and flexible motion with large deformation force, was difficult.

Maruyama reported the rapid cooling system utilizing a transient operation of a Peltier module. The transient operation of the Peltier module combined with cooled heat sink realized higher heat flux than steady state cooling operation of the Peltier module. Also, a thermoelectric actuator, which is utilizing the transient operation of the Peltier effect and two-way SME, was suggested. This actuator was expected to realize a rapid motion.

In the medical field, there are some problems on research field of artificial heart. The implantable artificial hearts currently utilized in Western countries have too large volume to implant it in the patient of small physique.

Also, infection is another problem on the connection between extracorporeal parts and implanted parts. Furthermore, there are serious problems on the pump type artificial heart such as thrombosis and hemolysis. Therefore, an artificial heart muscle system utilizing thermoelectric actuator push to assist weaken heartbeat is expected. A constriction of weaken cardiac muscle will be assisted by the motion of an actuator sewed on the weaken cardiac muscle. This application method can assist heartbeat without minding the problems on conventional artificial heart systems.

In this study, fabrication of the thermoelectric actuator, which will realize rapid motion under loading condition, and the evaluation of its performances were carried out in order to realize an artificial heart muscle utilizing a thermoelectric actuator.

Chapter 2. Estimation of Characteristics on Shape Memory Effect

In this chapter, fundamental performance of the SME was measured in order to comprehend the characteristics of SME and to discuss the utilization method of SMA into thermoelectric actuator.

All-round SME occured in Ti-51at%Ni generate 2% of strain in the temperature range 223K to 323K. The strain of all-round SME, which occurs over room temperature, was measured to evaluate the strain, which can be applied to thermoelectric actuator. Measurement of the strain over room temperature was carried out with constrain jigs with different sizes. As a result, 0.5% of the maximum strain over room temperature was found.

Fatigue of SME limits the application time of the actuator. The lifetime of Ti-51at%Ni is reported as 0.1million cycles, which is about 1day with 1Hz motion. On the other hand, the lifetime of Ti-Ni-Cu wire, produced from Toki Corporation, is reported as 30milion cycles. Therefore, extension of the lifetime of the actuator was expected with this SMA wire. The variations of lifetime and strains of this SMA wire were measured under constant loading conditions. For example, the decreasing of the lifetime was measured depending on the increment of loading stress from 50MPa to 150MPa. This result showed that the utilization of a certain numbers of SMA wires is effective for the extension of the lifetime of the actuator because of the reduction of the stress in one wire.

Efficiency of the SME, which is heated by the Joule heating and cooled by natural convection of air, was measured with the SMA wire. The laser displacement meter measured the strains of SMA wire loaded by the weight in order to calculate the efficiency of work made by SME. The maximum efficiency of 2.4% was measured under 22.05N.

Chapter 3. Heat Transfer Control of Thermoelectric Actuator Utilizing Ti-Ni Rod

In this chapter, the thermoelectric actuator utilizing SMA rod was fabricated and its performance was experimentally and numerically evaluated. Figure 1 is the concept of the thermoelectric actuator fabricated in this study. SMA rod was alternatively heated and cooled by the Peltier circuit, which consists on p-n types of thermoelectric semiconductors, electrodes and heat sinks made of copper alloys. Electrically insulating film is separating SMA rod from a conduction of electric current in order to avoid Joule heating during cooling by Peltier cooling. Figure 2 shows the structure of the fabricated thermoelectric actuator utilizing C-shaped heat sinks. In this structure, the electrodes and thermoelectric semiconductors are maintaining electrical and thermal connection

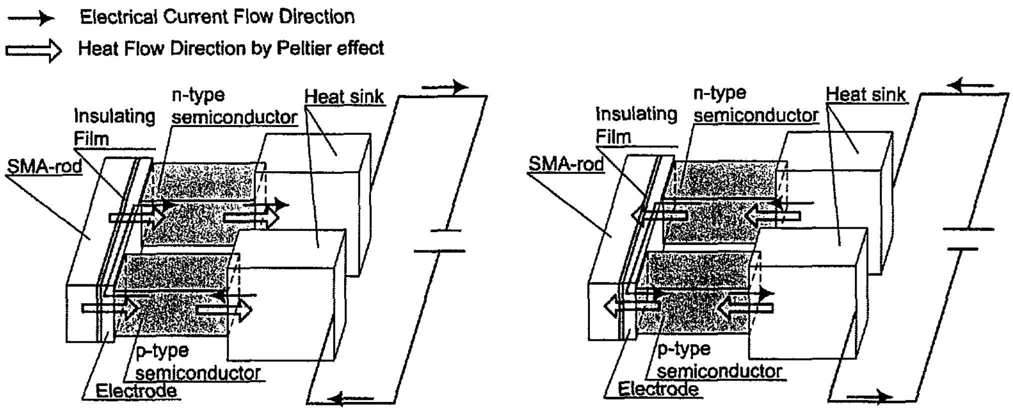

Figure 1 Concept of the thermoelectric actuator

by the mechanical contact in order to avoid the suppression on the bending motion of the SMA rod. As an experimental result, the actuator continuously bent and stretched in 1Hz with 0.1% strain under unloading condition. This strain value was 20% of the strain measured in chapter 2. Then, numerical simulation was carried out in order to evaluate heat transfer condition inside of the thermoelectric actuator. The structure of the actuator was one-dimensionally approximated along the heat transfer direction of the Peltier effect, which is dominant heat transfer effect in the thermoelectric actuator. The structure of the thermoelectric actuator includes mechanical contact maintaining electrical connection between thermoelectric semiconductor and electrode. The numerical simulation showed that the electrical resistance and thermal resistance of the mechanical contact have large influence on the temperature behavior of the SMA rod. This influence induced the small strain of the actuator found in the experiment. Therefore, the soldering connection between the thermoelectric semiconductors and electrodes were needed to increase the strain of the actuator.

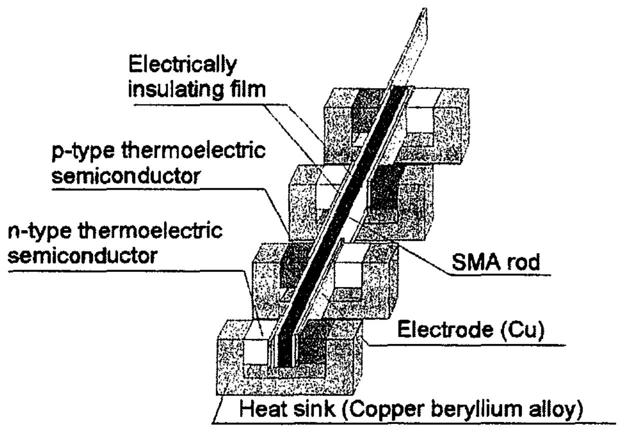

Figure 2 Structure of the thermoelectric actuator utilizing C-shaped heat sink

Chapter 4. Heat Transfer Control of Thermoelectric Actuator Utilizing Ti-Ni-Cu Wire

In this chapter, the thermoelectric actuator utilizing SMA wires were fabricated and evaluated its performance under constant loading conditions. The SMA wire, evaluated in Chapter2, has larger strain and smaller cross sectional area than the SMA rod, which have been utilized in the actuator developed in Chapter3. Therefore, the SMA wire is applied for the enhancement of strain and the downsizing of the actuator. Also, the Ω-shaped electrode was applied for the consisting of soldering, which joint thermoelectric semiconductors and electrodes, and flexible motion of the actuator. The actuator utilizing U-shaped heat sinks, shown in Fig. 3, is evaluated its performance under constant loading condition. In the experiment, the maximum strain in 1Hz motion of the thermoelectric actuator is 0.75%, which is larger than the strain measured in the actuator utilizing C-shaped heat sinks. Also, it was found that the efficiency in 1cycle of the actuator utilizing Peltier heating is higher than that of the actuator utilizing Joule heating.

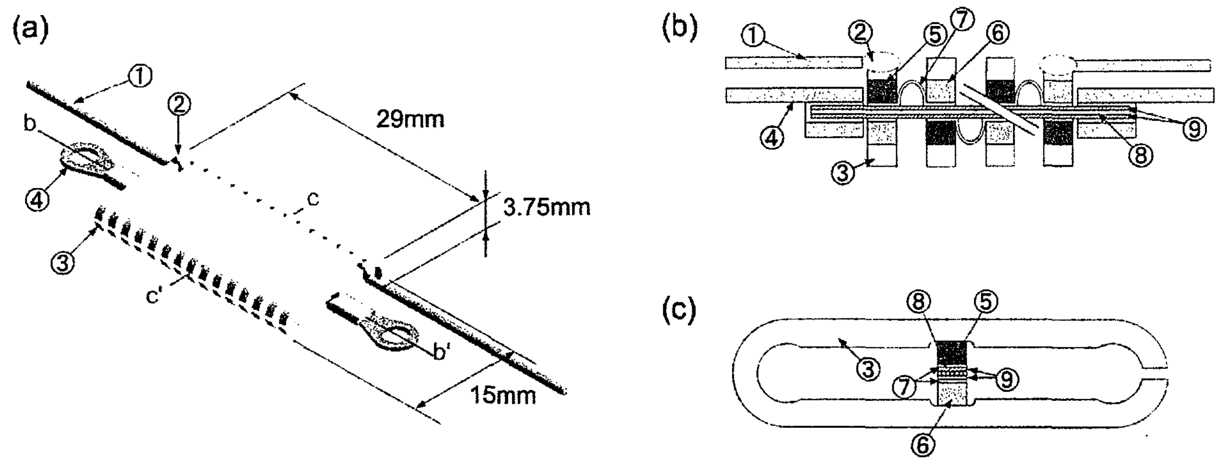

Figure 3 Structure of thermoelectric actuator utilizing SMA wires, (a) outside view, (b) b-b' cross sectional view, (c) c-c' cross sectional view: ①Lead for electrical input, ②Soldering joint, ③U-shaped heat sink, ④Clipping terminal, ⑤P-type thermoelectric semiconductor, ⑥N-type thermoelectric semiconductor, ⑦Ω-shaped electrodes, ⑧SMA wires, ⑨Electrical insulating film.

Chapter 5. Application of Thermoelectric Actuator in Medical Field

In this chapter, possibility on the application of the thermoelectric actuator as artificial heart muscle was experimentally evaluated and discussed. The force of the actuator utilizing U-shaped heat sinks was measured on the left ventricle model. Maximum force of 2.25N was measured with 100mmHg of inner pressure of the left ventricle model. Also, the thermoelectric actuators were sewed on the cardiac muscles of goats. Motions of the actuators on the heart of goats were tried to be measured. Unfortunately, the measurements were failed because of a poor waterproof and a separation of a soldering joint of a lead for electrical input. However, the flexibility and durability of Peltier circuit was confirmed because soldering joints of Peltier circuit had no failure on the active motion on the heart of goat.

Also, application method of the actuator is discussed. The thermoelectric actuator utilizing U-shaped heat sinks has possibility of utilization as the assisting device for the myocardial infarction. Also, the size of the actuator is quite small compared with the smallest pump type heart assist device which conventionally utilized.

Chapter 6. General Conclusion

In this chapter, the main conclusions obtained through this study were summarized.

論文審査結果の要旨

形状記憶合金は温度に依存し形状を変化させる形状記憶効果を有しており、アクチュエータの動作機構に応用されている。従来研究において見られる通電加熱および空冷を形状記憶合金の加熱冷却に用いた場合、冷却に時間がかかり反復動作が必要な応用は困難であった。電気の投入によりヒートポンプとして動作する熱電素子を形状記憶合金と組合せれば、より高速な形状記憶合金の動作が実現できる。一方、医学分野においては比較的小柄な体系の患者が利用可能な小型人工心臓の開発が望まれている。

本論文は、熱電素子と形状記憶合金を組合せ補助人工心筋への応用を目的として高速での動作を目標とした運動素子の製作と、その動作性能、応用に関する考察についてまとめたものである。

第 1 章は序論であり、本研究の背景と目的について述べている。

第 2 章では、運動素子の製作に用いた形状記憶合金における形状記憶効果のひずみ・疲労・効率の各特性を実験的に評価し、製作する運動素子の特性について考察し、形状記憶合金を運動素子として用いる際の留意点を明示している。

第 3 章では、形状記憶合金のロッド上に熱電半導体素子、電極およびヒートシンクから成るペルチェ回路を配置した構造を有する運動素子を製作し、実験と数値計算を用いてその動作性能を評価し、製作した運動素子が 1Hz での反復動作を無負荷条件下において実現可能であることを明らかにしている。これは、従来研究において見過ごされていた伝熱学的な問題を解消したことにより得られた新しい成果である。

第 4 章では、形状記憶合金のワイヤを用いた運動素子を製作し、実験的にその動作を評価し最大 20N の負荷条件下における 1Hz 動作を確認している。さらに通電加熱を用いた運動素子に比べて高効率な動作が実現可能なことを明らかにしている。これは、形状記憶合金を用いた運動素子について従来よりも高効率な動作機構であることを明らかにしたものである。

第 5 章では、製作した運動素子を用いて補助人工心筋として応用した条件下における性能を実験的に評価するとともに、その展望を考察している。製作した運動素子は従来の人工心臓と比較してはるかに小型なものであり、体内に埋め込み、心筋梗塞による発作などの緊急時に心機能を補助する装置としての応用に期待できることを明らかにしている。

第 6 章は結言である。

以上要するに本論文は、形状記憶合金と熱電素子を組合せた運動素子の製作し、負荷下において高速での動作を実現しており、その動作性能は補助心筋としての応用の実現に期待ができる。補助人工心筋への応用の可能性を述べており、医工学および伝熱工学の発展に寄与するところが大きい。

よって本論文は博士（工学）の学位論文として合格と認める。